SATCOM

QUARTERLY

Mobile • • • Micro • • • Personal

Jet Propulsion Laboratory No. 1 April 1991

Welcome — From the Managing Editor

The *Quarterly* has a new name and a new scope. The *SATCOM Quarterly* will broaden the perspective of its predecessor, the *MSAT-X Quarterly,* by reporting on current research in mobile, micro and personal communications technologies and highlighting the vital role satellites will play in turn-of-the-century telecommunications.

In addition, some new personnel have joined JPL's Communications Technologies Program. Most notably, Dr. Lance Riley, who has an extensive background in spacecraft telecommunications, is the new Program Manager. Lynn Polite has been replaced by Randy Cassingham, who has many years of experience with technical publications. Randy will be responsible for technical report production and distribution as well as editing the *Quarterly*. Lynn has returned to her previous career as a marketing analyst and has accepted a position with Kraft Foods in Chicago. All of us who had the pleasure of working with Lynn want to thank her for generating and maintaining a high level of interest in the Mobile Satellite Program. We wish Lynn and her family well and hope to see them on vacations back to California!

The start of a new Quarterly is an appropriate time to update our database, so please check your address label for accuracy. Contact Randy Cassingham if you have any changes or wish to request technical documents. All those who received the *MSAT-X Quarterly* will automatically receive the *SATCOM Quarterly*. And for your convenience, we have also listed on the back page the JPL contacts in specific technology areas.

Laura C. Steele

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Managing Editor

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The Satellite Communications (SATCOM) Program is managed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The goals of this Program are to develop advanced system concepts and technologies in the areas of mobile, micro and personal communications. A major thrust of the Program through the mid-1990s is the development of the mobile terminal to operate with NASA's Advanced Communications Technology Satellite.

A New Focus for the Quarterly

W. Rafferty, JPL

This premiere issue of the *SATCOM Quarterly* reflects the broadened scope of reporting on satellite communications (SATCOM) activities within the NASA-funded Communications Technologies Program at JPL. The *SATCOM Quarterly* replaces the *MSAT-X Quarterly* newsletter, which specifically detailed the activities of the NASA/JPL Mobile Satellite Experiment Program. The *MSAT-X Quarterly* was a successful part of NASA's goal to inform the various constituents of the telecommunications community about the promise, utility and key NASA-developed technologies of mobile satellite communications. Through the *MSAT-X Quarterly*, vital information on key developments was transferred to the telecommunications community. The *SATCOM Quarterly* shares many *MSAT-X Quarterly* goals, although this new quarterly's focus has been broadened beyond mobile communications.

SATCOM studies at JPL had sufficiently matured in 1990 to establish two new major research and development directions: mobile communications systems at Ka-band and, more generally, personal communications.

While 1990 marked the last year of L-band technology development for MSAT-X, new directions within the NASA's Advanced SATCOM Studies at JPL had sufficiently matured in 1990 to establish two new major research and development directions: mobile communications systems at Ka-band and, more generally, personal communications. The latter evolved first; it is aimed at bringing Ka-band satellite communications to the consumer level by exploiting available bandwidth and reduced equipment size.

Ka-band mobile systems took on particular urgency when it was decided to exploit NASA's Advanced Technology Communications Satellite (ACTS). It is believed that this push will aid in opening up the available Ka-band spectrum (where ACTS will operate) for the widely predicted need to support more mobile satellite users. In addition, 1990 was a year in which there was an explosion in mobile and personal communications concepts and related service filings with the Federal Communications Commission (FCC). A number of entrepreneurs, particularly in Europe and the United States, announced a "dizzying" array of new concepts to the telecommunications community. These ranged from personal terrestrial systems — such as CT2 in the United Kingdom — to a low Earth constellation of 77 satellites for a personal system conceived by Motorola Inc. in the United States. Developments have been rapid and have spawned even more new ideas and services at an equally fast pace. The recent worldwide trend in spectrum liberalization has encouraged these developments. This has resulted in the entry of some unexpected players such as Apple Computer Inc., which has requested radio spectrum (1.85–1.90 GHz) for personal communications networking for computer users.

A close look at these new developments will show many common service features and frequencies of intended operation. Moreover, it is clear that satellites and terrestrial services are targeting similar user needs. This will inevitably lead to a "merger" of ideas, providers, etc. However, certain technology challenges remain in both the ground and space segments, several of which are addressed by NASA's Satellite Communications Program. These challenges form the basis of the SATCOM work at JPL and at other NASA Centers. In particular, the

SATCOM Quarterly will report on JPL-led developments and on other significant developments as they affect this area.

Near-Term Focus

As mentioned previously, the *MSAT-X Quarterly* has ceased publication; the last issue, No. 26, was distributed during the first quarter of 1991. However, termination of the *MSAT-X Quarterly* does not signify the end of L-band NASA/JPL mobile satellite efforts. JPL is still involved with NASA in the launch negotiations for the first U.S. mobile satellite licensee holder and with the preparations for government experiments that will use satellite capacity bartered in exchange for the launch. Also, JPL is active in the area of direct broadcast satellite radio (DBS-R). The DBS-R system studies are being performed with the intention of submitting concepts to domestic and international review and rule-making bodies. In the summer of 1991, JPL hopes to demonstrate an L-band 20-kbps audio system using modified MSAT-X hardware. These and other related L-band activities will continue to be reported in the *SATCOM Quarterly.*

This issue has a number of articles relating to propagation effects, the fundamental challenge posed by satellite operation at Ka-band. Indeed, JPL has already focused considerable effort to understand these effects, as is true for other research centers in this field. Also in this issue is an article on NASA's Advanced Communications Technology Satellite (ACTS). ACTS is an important NASA program and is a major focus of Ka-band SATCOM work at JPL. Follow-up articles on ACTS will highlight major milestones in that program and in a number of JPL-led experiments and demonstrations using ACTS.

In upcoming issues, the *SATCOM Quarterly* will report regularly on developments in the design, development and demonstration of a prototype mobile terminal that will operate with ACTS. This activity, called the ACTS Mobile Terminal (AMT), is intended to be a test-bed for future commercial-oriented mobile system concepts and technologies. Other articles on ACTS will describe ultra-small aperture terminals, aeronautical terminals (for voice, data and video) and personal communications terminals. NASA/JPL interest in personal communications has resulted in a proposal to the FCC for a new class of satellite services at Ka-band, based on direct-to-user, low bit rate communications. This work has necessarily included system concept development and regulatory studies, both of which will be reported on in the *Quarterly.*

The *Satcom Quarterly* will be technical in nature and will feature articles on user studies and needs, economic and regulatory issues and industry developments.

While the *SATCOM Quarterly* will be technical in nature, articles on user studies and needs, economic and regulatory issues and industry developments will also be featured. First in this series will be an article on a personal communications market study that is currently in progress.

NASA has a long and distinguished presence in satellite communications as a technology innovator and leader. NASA launched the first relay satellite in the mid-1960s and has maintained its leadership ever since. MSAT-X and ACTS are examples of current NASA programs that are shaping the future of SATCOM. JPL is an eager partner with NASA in this telecommunications area and is committed to developing system concepts and technologies that will benefit the United States and telecommunications in general. The *SATCOM Quarterly* will be reporting on these developments in future issues.

NASA's Advanced Communications Technology Satellite Program

D. A. Olmstead, ACTS Program Manager, NASA Headquarters

With the launch of its Advanced Communications Technology Satellite (ACTS) in May 1992, the National Aeronautics and Space Administration will again demonstrate its commitment to the development of future satellite communications technologies and systems. ACTS is a flexible laboratory that will be used to validate a number of advanced communications technologies for future commercial use. Because of the experimental nature of the ACTS program, participating organizations will have an opportunity to demonstrate creative applications of a variety of revolutionary technologies that will be flown on the satellite.

ACTS has the technical ability to accommodate a wide array of data rates — from 2.4 kbps to 1 Gbps — in a variety of network architectures. In fact, it is ACTS' broad range of capabilities that makes this program so valuable to the continued development of communications satellite services.

Validating Key Technologies

The key technologies that will be validated as part of the ACTS program include

- Baseband processor (BBP) — a high-speed digital spacecraft regenerating switch that efficiently uses transponder capacity (in time and frequency) for routing individual circuit-switched messages.

- Ka-band components — used in the development of flight and ground terminal hardware at 30 and 20 GHz.

- Rain fade compensation procedures — techniques such as dynamic forward-error correction and rate adjustment that will be used to automatically overcome uplink and/or downlink signal level fades.

- Multiple beam antenna — a rapidly reconfigurable hopping and fixed spotbeam antenna, which is most useful in areas where traffic is widely disseminated geographically and where no single area has sufficient traffic to justify the use of a stationary spotbeam. Beam hopping aggregates the traffic from such regions, and the onboard switch permits full interconnectivity among all spots.

The ACTS system includes both flight and ground segments. The flight segment consists of the multibeam communications package and the spacecraft bus. In orbit, ACTS will "weigh" approximately 3,270 lbs and will measure 46.5 ft from tip to tip along the solar arrays and 30 ft from the edge of one antenna to the other. ACTS will be located in a geosynchronous orbit at 100° W longitude. Separate Ka-band antennas, each with horizontal and vertical polarization subreflectors, are provided for transmitting and receiving signals. The offset Cassegrain antenna system will provide two hopping spotbeam families plus three fixed spotbeams. A steerable antenna, part of the west scan sector (shown in Figure 1), will provide coverage to most of the Western Hemisphere. The multibeam communications package provides the means for receiving, processing, switching, amplifying and transmitting signals that carry high-speed digital communications traffic.

ACTS hopping beams provide the availability of high transmission rates on demand. The uplink transmission rate of the LBR-2 station is nominally 27 Mbps, whereas the LBR-1 is 110 Mbps; the downlink on both the LBR-1 and LBR-2 is 110 Mbps. These high rates can be extremely valuable to a data transmission user who has several hundred kilobytes per second or more to transmit. The hopping beam can be transmitted to the user at a dwell time

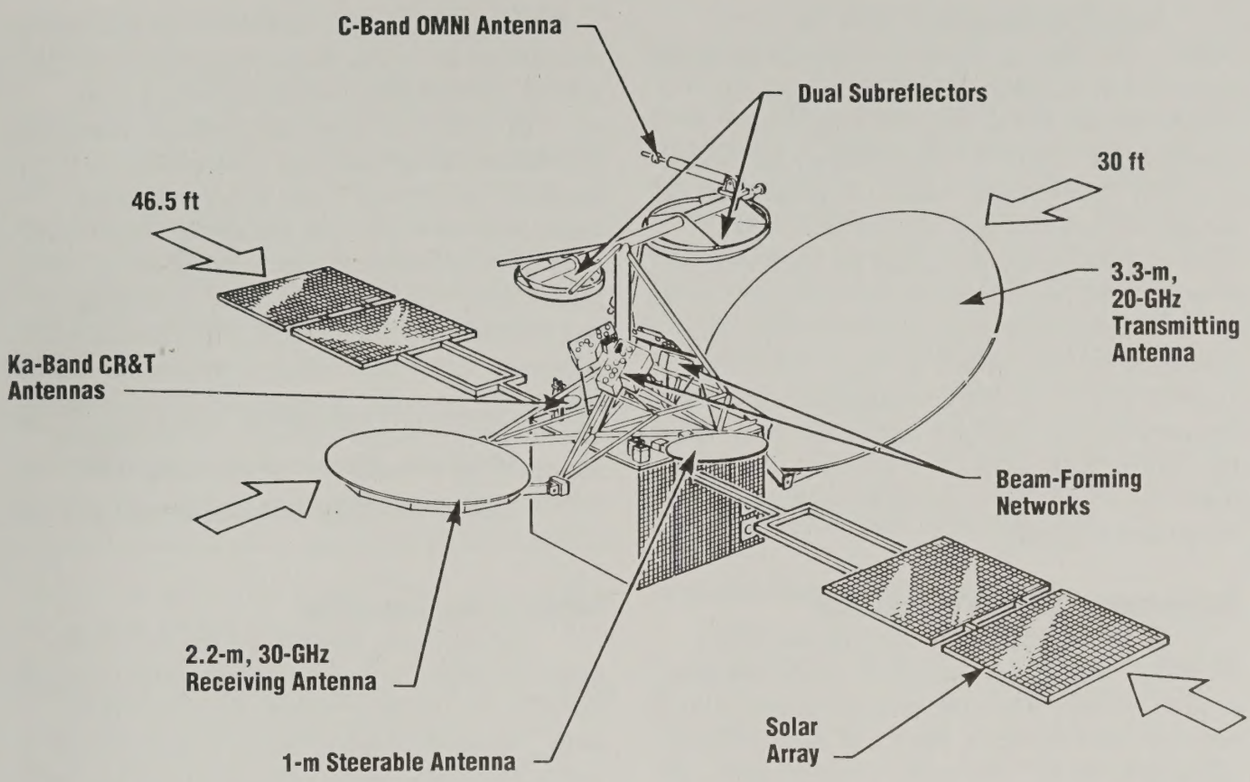

Figure 1. Spacecraft configuration showing position of ACTS' steerable antenna.

sufficient to transport data at a T–1 rate of 1.536 Mbps. The advantage of this technology is that in an operational system, the user will pay only for the connect time actually used and not for a full-time dedicated channel or line.

The ACTS ground segment consists of a spacecraft control center, the NASA ground station and the experimenter terminals. The General Electric (GE) satellite control center will be linked to the NASA ground station via terrestrial voice and data circuits. The GE C-band command, ranging and telemetry station in New Jersey will provide transfer orbit support and will serve as an operations backup to the satellite center. The NASA ground station, which will be located at NASA's Lewis Research Center, will include the master control station, a low burst rate (LBR) traffic and time division multiple access (TDMA) reference terminal, and a high burst rate (HBR) terminal. The LBR terminals will operate with the baseband processor, and the HBR terminal will operate with the microwave switch matrix.

Figure 2 shows the terminal operating capabilities supported by the current ACTS configuration; also shown are the ground terminals necessary for each experiment execution. In addition to supporting high data rate communications using very small aperture terminals (VSATs), satellites based on ACTS technologies will be suitable for the transmission of Ka-band mobile traffic, including higher data rate aeronautical, personal and maritime communications. Universal, on-demand broadband access is an emerging market requirement that will be cultivated via experimentation on ACTS. Gigabit rate networks for scientific visualization or supercomputer interconnection and fiber network restoration are also candidate applications for ACTS-derived technology. High resolution video imagery, such as high definition television and cable/satellite hybrid and satellite/cellular hybrid networks, will also fall within the capabilities of an ACTS-like satellite [1].

Expanding Satellite Communications Capabilities

ACTS represents NASA's return to satellite communications development and will demonstrate the feasibility of a variety of technologies that will be incorporated into future operational satellites. The ACTS demonstration and experiment program, and the verification of ACTS innovative technologies that are applicable to various satellite communications frequency bands, hold the key to continued industry growth and improved customer service in the satellite communications field.

Future operational systems like ACTS could add a new dimension to communications services by combining the technologies of satellites and fiber optics. Although fiber systems offer excellent performance for point-to-point, high-volume "trunk" communications, advanced satellites will be competitive with fiber systems in capacity, cost performance and reliability for point-to-point services, particularly in rural and remote regions. More important, advanced satellite links can team with fiber systems to expand the communications capabilities of users who are not part of the main fiber backbone. Without satellite connections, these users would not have access to high-capacity transmission media.[1]

Demonstrating Tomorrow's Technology

ACTS, like previous and current NASA missions, is an experimental program designed to give industry and academia an opportunity to test and demonstrate a variety of new technology applications. The ACTS program office at NASA Headquarters and the project office at the Lewis Research Center are working with industry and academia to identify the most promising commercial applications of ACTS technology.

Among the many new technologies being considered for ACTS demonstrations are high definition television; broadband integrated services digital network (B-ISDN); international mobile and micro-terminal communications; domestic thin-route, mesh VSAT networks; education networks; fast packet networks, and multiple rate networks (including browse and burst). The application of these technologies will certainly be augmented, and perhaps even superseded, by many other activities that could eventually be undertaken by potential customers, communications carriers and equipment suppliers. Nevertheless, they convey the importance, the dimensions and the excitement of this enterprise.

Increasing User Capabilities

Technologies devised by the ACTS program are likely to narrow the gap separating the information services "haves" from the "have nots." Because of the wideband transmission needs associated with the information processing technologies that will be perfected in the 1990s, there is concern that these capabilities will be utilized only by users in limited areas who are connected by fiber-optic cable. However, advanced communications satellites incorporating ACTS-validated technologies will expand the availability of wideband transmission and, subsequently, increase access to the

[1] *For more information on future communications satellites, see S. J. Campanella, "Communications Satellites: Orbiting into the 90's,"* IEEE Spectrum, *August 1990.*

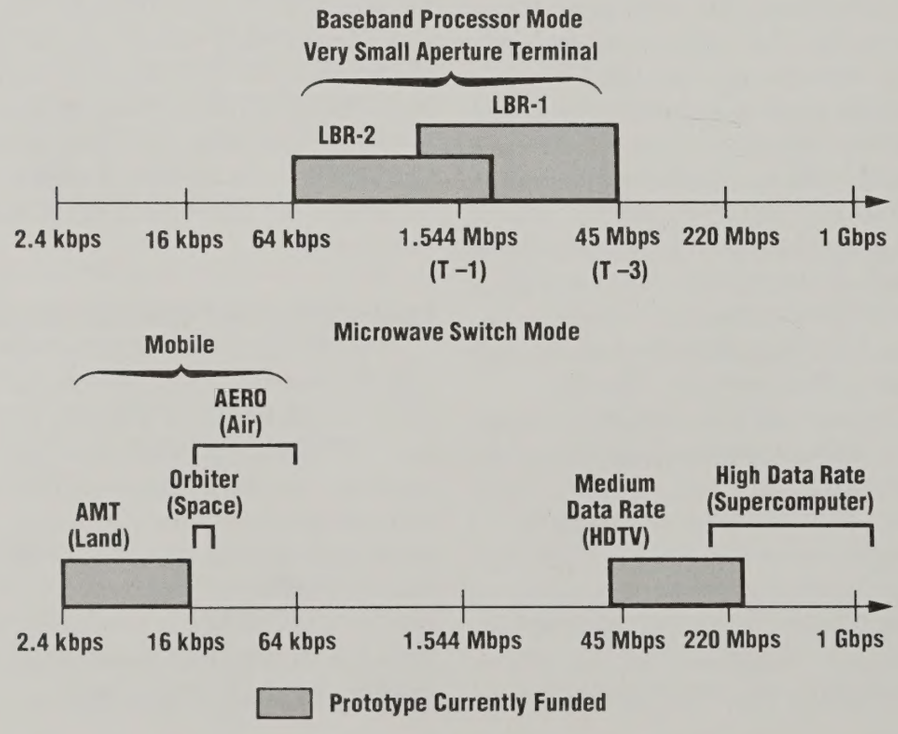

Figure 2. ACTS ground terminal operating capabilities for communications technologies.

services and advantages offered in the "Information Age."

The trend in satellite communications is toward small Earth stations and higher frequency bands. This combination permits major advancements in convenience, performance and cost-effectiveness. The Earth stations planned for the ACTS Ka-band voice networking transmission will be considerably smaller and more portable than the current Ku-band VSATs that are within a mesh, hubbed network. These new highly transportable terminals will be serviced on demand by ACTS' hopping spotbeams; this will greatly expand the range of applications offered and will improve many services such as newsgathering and portable personal communications.

ACTS' high-power spotbeams can provide wide bandwidth services to aircraft, low Earth orbiting spacecraft and maritime vessels.

Going one step further, the ACTS high-power spotbeams can provide relatively wide bandwidth services to mobile units such as aircraft, low Earth orbiting spacecraft and maritime vessels. If used in the international aeronautical mobile arena, ACTS technology will support a large number of "public correspondence" users on a single aircraft. (The current system designs using L-band can only support two voice channels that are shared by passengers and crew.)

Another mobile application with good commercial potential is the transmission of "viewer quality" 3-Mbps National Television Standards Committee video programming, which can be demonstrated via ACTS to a 0.8-m antenna on board maritime vessels using video compression equipment such as the codec developed by Compression Laboratories, Inc.

In addition to newsgathering, aeronautical and maritime communications, the ACTS experiments will be able to address broad new potential markets, including municipal health and safety services, law enforcement activities, disaster assessment and relief, vehicle tracking and routing, and even some forms of personal communications.

The development and application of technologies, such as ACTS, that provide wide bandwidth connectivity for remote and rural areas are critical to the worldwide growth of information systems. Of importance to rural and remote areas will be the ability of these advanced technologies, specifically satellite technology, to provide wide bandwidth access. This can be done at lower cost with ACTS technologies because of its traffic aggregation and on-demand circuit assignment features. Unlike the wide bandwidth transmission provided by optical fiber, wideband satellite transmission includes any area — regardless of its terrain or geographical location — within the satellite's hemispherical field of view.

Increasing Commercial Opportunities

Signs of ACTS technology being adapted to the commercial realm can already be seen in the United States. Several of the technologies that will be flown on ACTS, including the baseband processor and Ka-band components, will be used commercially in future satellite systems. Recently, Motorola, Inc., one of the major contractors on ACTS, announced the introduction of its Iridium system, which will be based on 77 low Earth orbit communications satellites to provide global coverage for data and cellular telephone communications.

In addition, Norris Satellite Communications applied to the Federal Communications Commission for authority to construct and operate a Ka-band satellite system. As a result of experimentation with ACTS, this system will provide follow-on capacity for fixed satellite services users as well as for general satellite services.

The ACTS program represents a unique opportunity for end users, service providers and equipment manufacturers to assess the feasibility of new applications and new ways of providing existing applications. No single application or demonstration would be sufficient to prove the power and flexibility of the system. It is, therefore, incumbent on the experimenters to push ACTS to its technological limits.

Reference

[1] F. M. Naderi and S. J. Campanella, "NASA's Advanced Communications Technology Satellite (ACTS): An Overview of the Satellite, the Network and the Underlying Technology," paper presented at the 12th AIAA Conference, Arlington, VA, March 1988.

ACTS Propagation Study Planning and Implementation Program

D. Chakraborty, JPL

The purpose of the Advanced Communications Technology Satellite (ACTS) is to demonstrate the feasibility of the Ka-band (30/20 GHz) spectrum for satellite communications. ACTS incorporates a number of innovative schemes — such as time division multiple access (TDMA), microwave and baseband switching, onboard regeneration and adaptive application of coding during rain fade conditions — that will help maintain U.S. leadership in satellite communications.

The success or failure of the ACTS experiment will depend on how accurately the rain fade statistics and fade dynamics can be predicted in order to derive an appropriate algorithm that will combat weather vagaries for links with small terminals, such as very small aperture terminals (VSATs) where the power margin is at a premium.

This article describes the planning process and hardware development program that will comply with the recommendations made by the ACTS propagation study groups.

ACTS Propagation Terminal Development Plan

A plan for the ACTS propagation terminal was initiated at the first ACTS Propagation Studies Workshop, November 28–29, 1989 [1]. The workshop's goal was to develop an ACTS propagation studies program and to propose a set of recommendations for propagation studies and experiments that would use ACTS. Recommendations were based on the group's assessment of the need for propagation data and configuration and the number of propagation terminals that would be required. The group also proposed guidelines on measurement parameters and requirements. These guidelines specify how the terminals should be configured so they can record the following propagation and meteorological parameters:

- 20-GHz beacon receive signal level
- 27-GHz beacon receive signal level
- 20-GHz radiometric sky noise temperature
- 27-GHz radiometric sky noise temperature
- Point rain rate near the terminal
- Atmospheric temperature at the Earth's surface
- Atmospheric humidity at the Earth's surface.

In response to the recommendations concerning propagation terminals, a two-phase plan has been devised. In phase 1, a terminal prototype will be developed; in phase 2, eight terminals will be manufactured for distribution to ACTS propagation experimenters.

The ACTS propagation receiver terminal will consist of a common antenna, a dual-channel receiver, a dual-channel radiometer and a data acquisition system. The terminal will also be equipped with meteorological recorders for measuring the point rain rate and the atmospheric temperature and humidity. Provisions will be made for a high bit rate (HBR) signal output at a convenient intermediate frequency (IF) in the receiver subsystem [2]. For example, when transmitted in a continuous wave mode via the spacecraft's steerable antenna, the HBR channel power will permit

Because a narrowband digital receiver can track a beacon signal in a bandwidth of about 10 Hz, a small antenna (1 m) can be used to maintain a 20-dB fade margin.

propagation measurements outside the continental United States. Therefore, this provision will facilitate experiments in the Arctic and the Tropics.

System Implementation

ACTS beacon frequencies are subjected to fluctuations, mainly due to onboard oscillator drift. The worst-case frequency uncertainty for a 15-minute period could be as high as ±555 Hz in the 20-GHz beacon and ±757 Hz in the 27-GHz beacon. Therefore, the ground receiver design has to accommodate this uncertainty. Both acquisition time and phase noise constrain the lower limit in the detection bandwidth of the receiver. On the other hand, wider bandwidth receivers allow faster acquisition, but with a penalty in the system margin.

Commercial receivers or spectrum analyzers (Hewlett-Packard 3588-A) or selective level meters (Hewlett-Packard 3586-C) will satisfactorily track the beacon signal with a detection bandwidth of about 100 Hz, which will require larger antennas (1.8 m or larger) to provide a 20-dB fade margin.

On the other hand, a narrowband digital receiver could track the beacon signal in a detection bandwidth of about 10 Hz, which will permit usage of a small antenna (1 m) to maintain a 20-dB fade margin. However, this digital receiver design could impose development cost, delay and operational uncertainty.

ACTS Beacon Characteristics

The principal characteristics [3] of the beacons are shown in Table 1.

Table 1. Characteristics* of the ACTS beacons

Parameter	27-GHz beacon	20-GHz beacon
Number of beacons	1	2
Frequency (polarization)	27.505 GHz ±0.5 MHz (V)	20.185 GHz ±0.5 MHz (V) 20.195 GHz ±0.5 MHz (H)
Function	Uplink fade measurement	Telemetry
Modulation	None	Yes (FM & PCM)
Nominal radio frequency output (dBm)	20	23
Nominal effective isotropic radiated power (dBW)	16	19
Operating temperature (°C)	–10 to +55	–10 to +55
Frequency stability	±10 parts per million over 2 years at constant temperature ±1.5 parts per million over 24 hours for temperature range –10°C to 55°C	
Output power stability	±1.0 dB over 24 hours ±2.09 dB over full mission	
Phase noise	–49 dBC/Hz @ 50 Hz –80 dBC/Hz @ 3000 Hz	–51 dBC/Hz @ 50 Hz –92 dBC/Hz @ 19 kHz

**Most of the characteristics shown have already been met in actual spacecraft hardware measurements [4].*

Link Calculations

Based on the frequency uncertainty and the receiver development status, two different antenna sizes have been considered: 1.8 m and 1 m. The link calculations based on these two antenna sizes are shown in Table 2.

If commercial receivers, spectrum analyzers or selective level meters are used, they will require 1.8-m, or larger, antennas. On the other hand, narrowband digital receivers, if available, will perform satisfactorily with 1-m antennas for a dynamic range of 20 dB.

Table 2. Link calculations

Beacon frequency band (GHz)	27.0	20.0	27.0	20.0
Antenna size (m)	1.8	1.8	1.0	1.0
Antenna gain (dB)	52.5	48.5	47.4	43.4
Nominal beacon effective isotropic radiated power (dBW)	16.0	19.0	16.0	19.0
Radio frequency losses (dB)	2.0	1.8	2.0	1.8
Modulation loss (dB)	—	3.2	—	3.2
Path loss at 30 deg elevation (dB)	215.0	212.0	215.0	212.0
Total loss (dB)	217.0	217.0	217.0	217.0
Low-noise-amplifier noise figure (dB)	4.2	3.5	4.2	3.5
Receive G/T (dB/K)	22.5	19.6	17.4	14.5
Power received at low-noise-amplifier input (dBW)	–148.5	–149.5	–153.6	–154.6
Carrier-to-noise density (dB-Hz)	50.1	50.2	45.0	45.1
Margin above 10-dB threshold (dB)	40.1	40.2	35.0	35.1
Recommended dynamic range (dB)	20.0	20.0	20.0	20.0
Allowable detection bandwidth (Hz)	102.0	104.0	31.0	32.0

Receiver Hardware

A functional block diagram of the proposed ACTS terminal is depicted in Figure 1. The diagram shows the common antenna and a dual-polarized feed for polarization separation. Normally, the 20-GHz beacon will be horizontally polarized; however, occasions may arise when the polarization will be changed to vertical polarization, the same as the 27-GHz beacon. Under this condition, the diplexer will separate the two beacon frequencies.

Two separate low-noise amplifiers (LNAs) are proposed; the LNA outputs are down-converted to first IF stages, which then feed two separate beacon receive channels. Second and third IF stages are included in the receivers. The receiver outputs are then fed to the data acquisition system, which processes the raw data along with the radiometer output and environmental data such as ambient temperature, rain gauge data, barometric pressure,

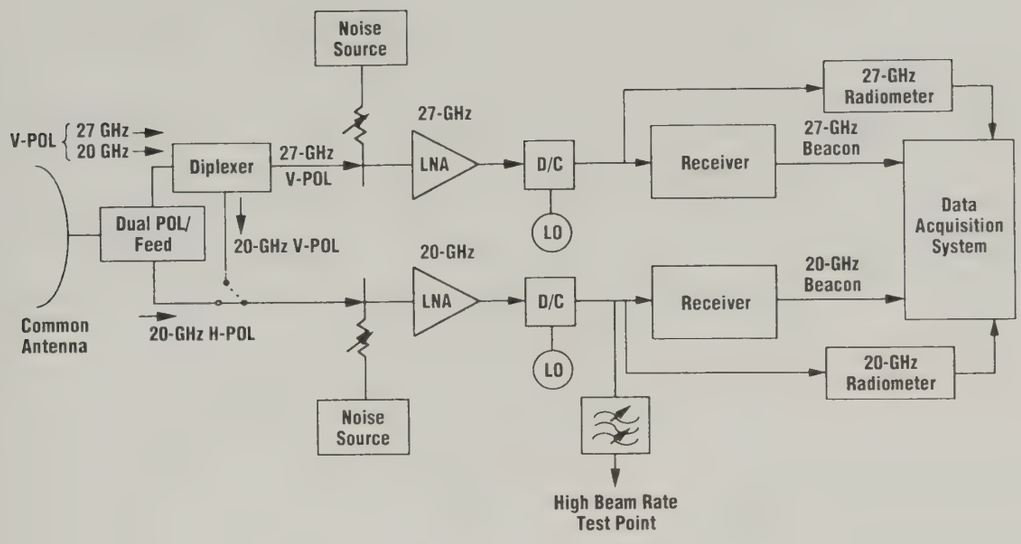

Figure 1. A functional block diagram of the ACTS propagation terminal

humidity, wind velocity/direction and rain temperature. These raw data are recorded on hard disks for further analysis.

The HBR test point will allow beacon signal measurements outside the continental United States if the HBR transmitter is switched via the steerable spotbeam antenna with no modulation applied to the carrier.

Proposed Beacon Location

The ACTS propagation working groups have recommended possible locations for the beacon-receive terminals:

Climatic Zone	Location
B_2	Colorado
C	Western Washington
D_1	Michigan
D_1	New Hampshire
D_3	North Carolina
E	Florida
F	California
A*	Arctic
G*	Tropics
H*	Tropics

**Using steering antenna and HBR carrier without modulation.*

Conclusion

Plans for the development of ACTS propagation terminals comply with most of the recommendations outlined by the propagation study groups. The envisioned prototype design and fabrication will be completed by early 1992, followed by production of eight terminals to be completed by late 1992.

References

[1] Presentations of the First ACTS Propagation Studies Workshop, JPL internal document D-6918, December 15, 1989.

[2] F. Davarian, F. Pergal, D. Chakraborty and W. Stutzman, "ACTS Propagation Terminal Prototype Planning and Design." In Proceedings of the Fourteenth NASA Propagation Experimenters Meeting and the ACTS Propagation Studies Miniworkshop, *F. Davarian, ed., JPL Publication 90-27, pp. 178–202, July 1, 1990.*

[3] F. M. Naderi and S. J. Campanella, "NASA's Advanced Communications Technology Satellite (ACTS): An Overview of the Satellite, the Network and the Underlying Technologies," AIAA Proceedings, *no. 88-0797, 1988.*

[4] F. Gargione, "Spacecraft Beacon Characteristics," Presentations of the First ACTS Propagation Studies Workshop, JPL internal document D-6918, pp. 35–65, December 15, 1989.

PASS Rain Attenuation Compensation Techniques and an Assessment of Service Availability

M. K. Sue, JPL

The Personal Access Satellite System (PASS) is a satellite-based personal communications concept for the 21st century [1–4]. PASS terminals employ a 30-GHz (Ka-band) uplink and a 20-GHz (K-band) downlink. These operating frequencies were selected because of the large available bandwidth and the potential for enabling the development of small, highly mobile user terminals; both factors are critical to the success of PASS.

Unfortunately, these frequency bands are sensitive to rain attenuation. This article discusses rain compensation techniques proposed for PASS and examines their impacts on link performance. It should be noted that various types of user terminals with different sizes and capabilities have been conceived for PASS; this article addresses only the small, hand-held basic personal terminals (BPTs).

PASS Rain Compensation Techniques

A combination of uplink power control and an adjustable data rate is used to combat rain attenuation. Uplink power control is only feasible for the large, fixed supplier terminals. When increased uplink power from the suppliers fails to fully compensate for rain degradation in the forward (supplier-to-user) direction, the data rate is reduced to close the link. Uplink power control is not available for the BPTs due to their limited power capability. Instead, the return (user-to-supplier) link only uses the variable data rate technique to compensate for rain attenuation. In particular, when rain fades are detected, the data rate is reduced by successive factors of 2 until link reliability is assured.

These rain compensation schemes will result in a reduction of service quality or even the termination of certain services during severe rain events. A quantitative assessment of the impacts on service availability is given in the next section.

Desired Service Availability

Link or service availability is a measure of system performance. Rain attenuation affects link availability; hence, a sufficient rain margin must be provided to maintain a desired link availability. Business-oriented and safety-related systems usually require an extremely high availability (e.g., 99.9% or better); at Ka-band, the corresponding rain margin would be prohibitively large. Since PASS is fundamentally a personal communications system, it can tolerate a relatively lower service availability. The design goal is to maintain 95–98% link availability for the baseline personal communications service, i.e., 4.8 kbps voice.

Estimated Rain Attenuation

Rain attenuation varies with the locations of the PASS terminals in the continental United States (CONUS) due to variations in local rainfall statistics and in elevation angles. To demonstrate this quantitatively, five locations in CONUS were selected for analysis: Seattle, Washington; Los Angeles, California; Mobile, Alabama; Miami, Florida; and Portland, Maine. These sites approximately represent the four corners of CONUS and one southern location. The percentage of the year that a given attenuation is exceeded for a particular terminal and

satellite location has been computed using a rain model developed by Manning [5]. The resulting data are shown in Figures 1 and 2 for the downlink frequency (20 GHz) and uplink frequency (30 GHz), respectively. These figures show that 99.9% of the time, the rain attenuation will not exceed 20–30 dB; by comparison, 98% of the time, rain attenuation will not exceed 1.0 dB at 20 GHz and 2.5 dB at 30 GHz.

Forward Link Analysis

To facilitate this discussion, Table 1 shows a clear-sky link budget for a voice channel at 4.8 kbps. It should be noted that based on the current design, the data rate in the forward direction is 100 kbps, which includes a number of time-multiplexed channels, at 4.8 kbps each and the necessary signalling overhead. The effects of rain attenuation and link availability

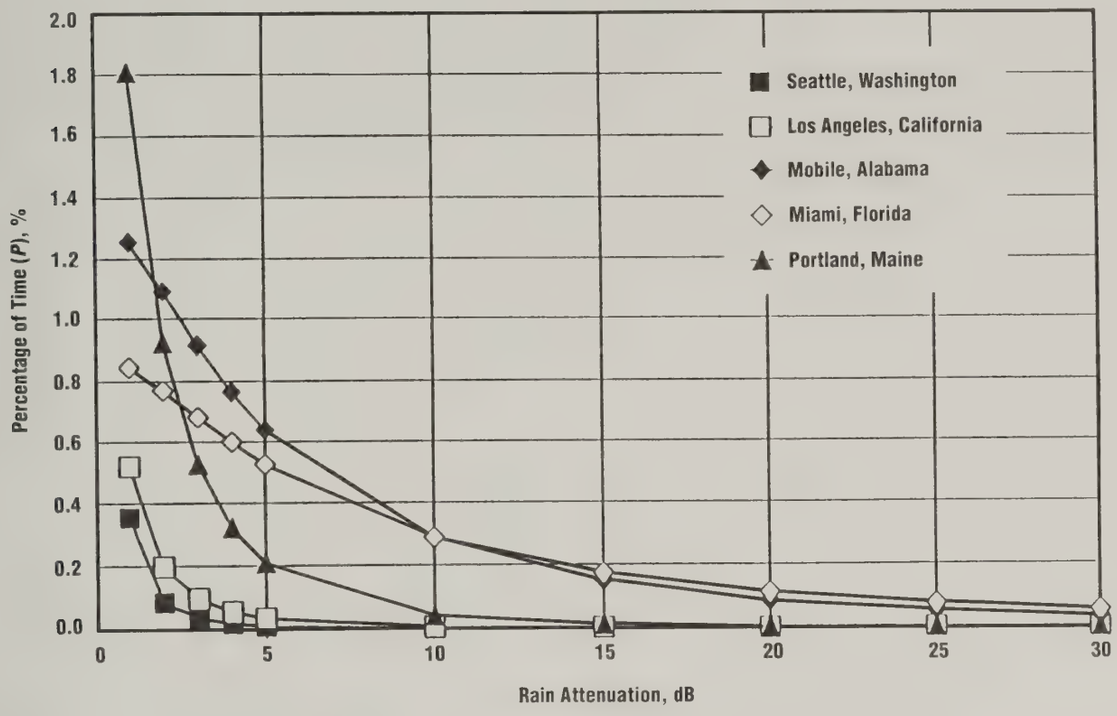

Figure 1. Rain attenuation for downlink frequency (20 GHz) at five locations (satellite located at 95° W; *P* = percentage of time attenuation is exceeded).

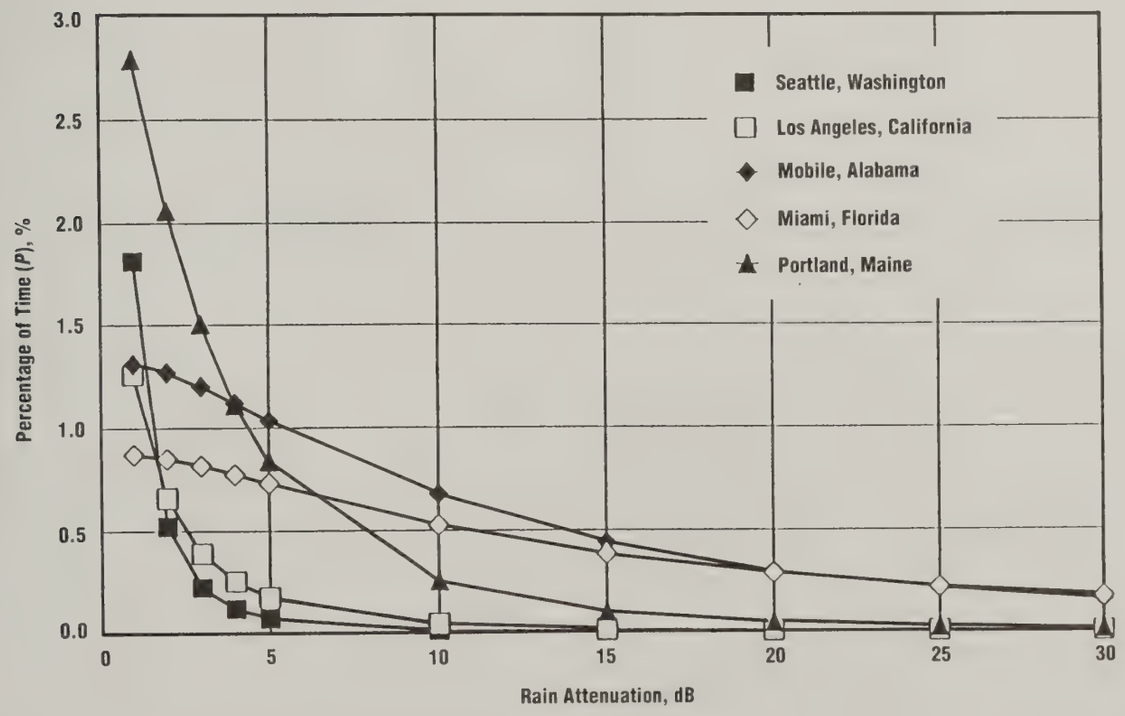

Figure 2. Rain attenuation for uplink frequency (30 GHz) at five locations (satellite located at 95° W; *P* = percentage of time attenuation is exceeded).

Table 1. Forward link budget for basic personal terminals (4.8 kbps voice, clear sky, 1.0^{-3} BER)

Link parameter	Supplier to satellite	Satellite to user
Transmit power dBW	–3.0	–8.3
Circuit loss, dB	–1.0	–1.5
Antenna gain, dBi	57.5	52.5
EIRP, dBW	53.5	44.2
Space loss, dB	–214.0	–210.5
Frequency, GHz	30.0	20.0
Edge of beam loss, dB	–3.0	–4.0
Receive antenna gain, dBi	26.9	19.3
Received signal power, dBW	–137.9	–154.3
System noise temperature, dBK	28.1	28.2
Received N_o, dBW/Hz	–200.5	–200.4
Received C/N_o, dB-Hz	62.6	44.5
End-to-end C/N_o, dB-Hz	—	44.4
Modem/radio loss, dB	—	–1.5
Required Eb/N_o, dB	—	3.0
Data rate, kbps	4.8	4.8
Required C/N_o, dB-Hz (voice)	—	39.8
Link margin, dB	—	3.0
Link variation statistics mean, dB	—	0.0
1-σ Link margin deviation, dB	—	1.0

are assessed based on an equivalent voice channel at 4.8 kbps. Table 1 shows that the forward link is downlink-limited, i.e., the overall (end-to-end) C/N_0 is essentially determined by the downlink C/N_0. The clear-sky link margin is 3.0 dB with a 1-sigma variation of 1 dB.

In the forward direction, rain attenuation is larger on the uplink than on the downlink. Fortunately, uplink rain attenuation (2.5 dB) can be fully compensated by uplink power control; therefore, it will not affect the overall link performance.

Although downlink rain attenuation is smaller, it has two adverse effects: it causes an increase in system noise temperature and in signal attenuation. For systems with a very low system noise temperature, the first effect is more pronounced than the second and can result in significant performance degradation. The operating system noise temperature of PASS terminals is approximately 650 K. The relatively

high noise temperature makes these terminals insensitive to the rain-induced increase in sky noise temperature, as indicated in Figure 3. Figure 3 shows the total signal-to-noise ratio (SNR) degradation as a function of rain attenuation for selected values for the receiving system noise temperature. The total SNR degradation includes the combined effects of signal attenuation and increased system noise temperature. As evident in this figure, the total SNR degradation is caused mainly by signal attenuation for typical PASS user terminals.

Two key parameters affect service availability. The first is clear-sky link margin variation x (dB). Link margin variation is a result of the variation in individual link parameters such as transmit power, antenna pointing error and thermal noise. Link margin variation can be modeled as a Gaussian random variable with mean μ_x and variance σ_x^2. The second parameter is rain attenuation y, which has the well known log-normal probability density function (pdf) [5].

Ignoring the effects caused by an increase in system noise temperature, the total link attenuation due to the combined effects of x and y is given by

$$z = \begin{cases} x & \text{no rain} \\ x + y & \text{during rain} \end{cases} \quad (1)$$

The pdf of x, $p_x(x)$, is given by

$$p_x = \frac{1}{\sqrt{2\pi}\ \sigma_x} \exp\left(-(x - \mu_x)^2 / 2\sigma_x^2\right) \quad (2)$$

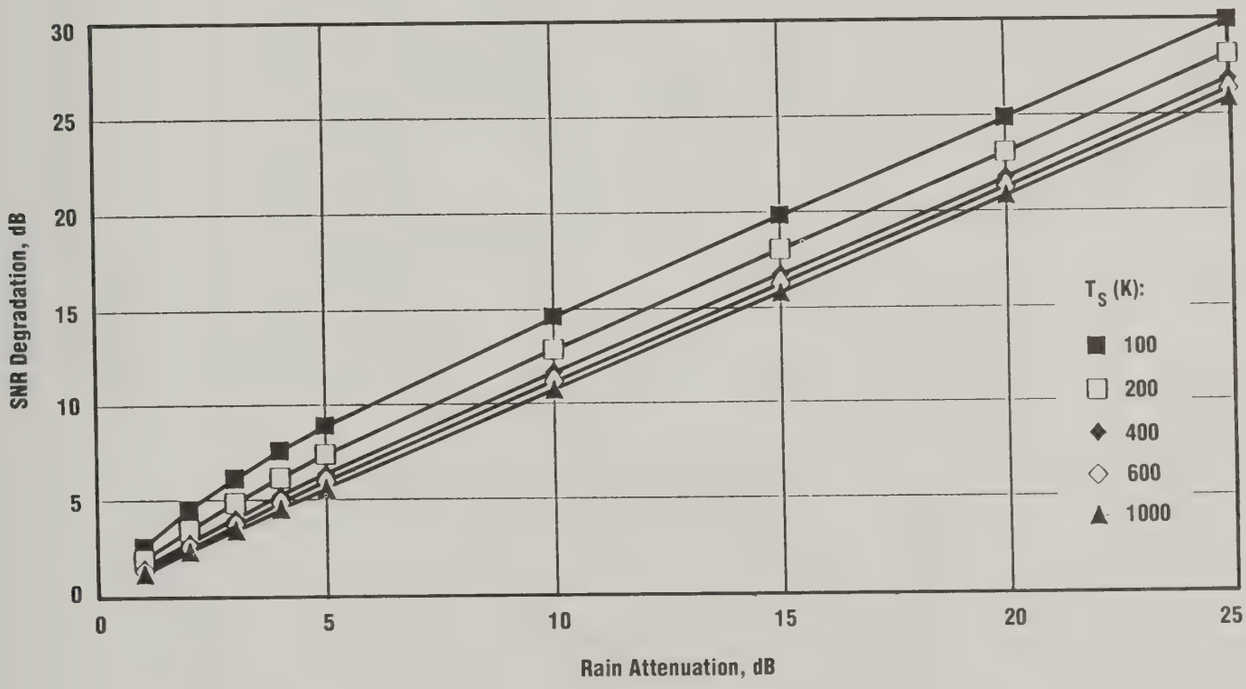

Figure 3. Total SNR degradation versus rain attenuation with clear-sky receiving system noise temperature (T_s) as a parameter.

The pdf of y that can be derived from its log-normal pdf is given by

$$p_y(y) = \frac{1}{\sqrt{2\pi}\ \sigma_{\ln(y)}\ y} \exp\left(-(\ln(y) - \mu_{\ln(y)})^2 / 2\sigma^2_{\ln(y)}\right) \quad (3)$$

where $\mu_{\ln(y)}$ is the mean of $\ln(y)$, and $\sigma^2_{\ln(y)}$ is the variance of $\ln(y)$. Assuming that x and y are independent, the conditional pdf of z during rain is given by

$$p_z(z|\,rain) = p_x(x) * p_y(y) \quad (4)$$

where * denotes convolution. In the absence of rain, the conditional pdf of z is identical to that of x. The total probability of z is obtained by averaging the two conditional probabilities with and without rain:

$$p_z(z) = (1 - P_0)\ p_x(x) + P_0\ p_z(z|\,rain) \quad (5)$$

where P_0 is the probability that rain occurs over any portion of the propagation path. The link availability for a given link margin can then be obtained by integrating $p_z(z)$.

The above analysis is used to estimate the service availability for three locations: Mobile, Alabama; Miami, Florida; and Portland, Maine. The first step is to determine rain attenuation and clear-sky link variation statistics. Rain attenuation statistics are computed using [5]; it is assumed that the satellite is located at 95° W longitude. Using a spreadsheet link design program, statistics for the clear-sky link variation are computed by specifying the favorable and adverse tolerances and the associated pdf for each link variable. These statistics are included in the link budget table and are tabulated in Table 2, along with the rain attenuation statistics.

Figure 4 shows, for Portland, Maine, the pdf of x, the pdf of y, the conditional pdf of z during rain, the total pdf of z and their relationship. The link availability obtained from Figure 5 gives the percentage of time that the total link attenuation exceeds a given link margin. As indicated, the 3.0-dB link margin would provide approximately 99% availability. (Note that the effect of increased system noise temperature has not been included in Figure 5.) For the range of BPT service availability, an increase in system noise temperature will not result in more than 0.4-dB degradation based on the three locations examined. Allowing a pessimistic 0.5 dB to account for the effect of increased system noise temperature, the resulting link availability would be approximately 98%.

Return Link Analysis

A clear-sky link budget for the return direction, with a clear-sky link margin of 3.0 dB and σ_x equal to 1.0 dB, is shown in Table 3. The return link is basically uplink-limited, whereas the forward link is downlink-limited. Rain attenuation on the downlink, which is less than 1.0 dB approximately 98% of the time, would have negligible impacts (less than 0.1 dB) on overall link performance.

Service availability for the return link is mainly determined by uplink rain attenuation and variations of link parameters. Ignoring the

Key parameter	Miami, Florida	Mobile, Alabama	Portland, Maine
$\mu_{\ln(y)}$, dB	6.5	4.8	1.2
σ_y, dB	1.0	0.9	1.0
P_o, %	0.9	1.3	3.2
μ_x, dB	0.0	0.0	0.0
σ_x, dB	1.0	1.0	1.0

Table 2. Key parameter values for the forward link

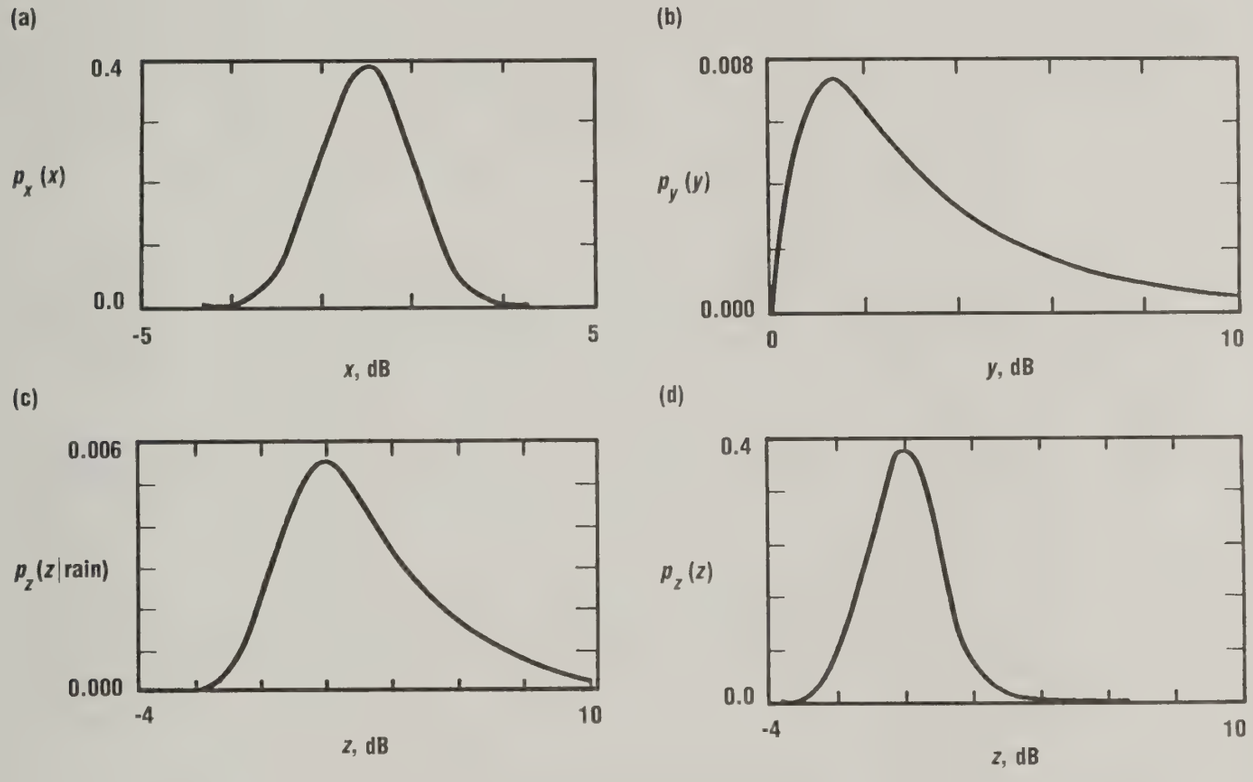

Figure 4. The $p_x(x)$, $p_y(y)$, $p_z(z)$ and their relationship for Portland, Maine; (a) the pdf of clear-sky link variation x; (b) the pdf of rain attenuation y; (c) the pdf of total link attenuation z conditioned on rain: $p_z(z \mid \text{rain}) = p_x(x) * p_y(y)$; (d) the total pdf of z averaged over rain and no rain cases: $p_z(z) = (1-p_o)\,p_x(x) + p_o p_z(z \mid \text{rain})$; p_o = probability of attenuation.

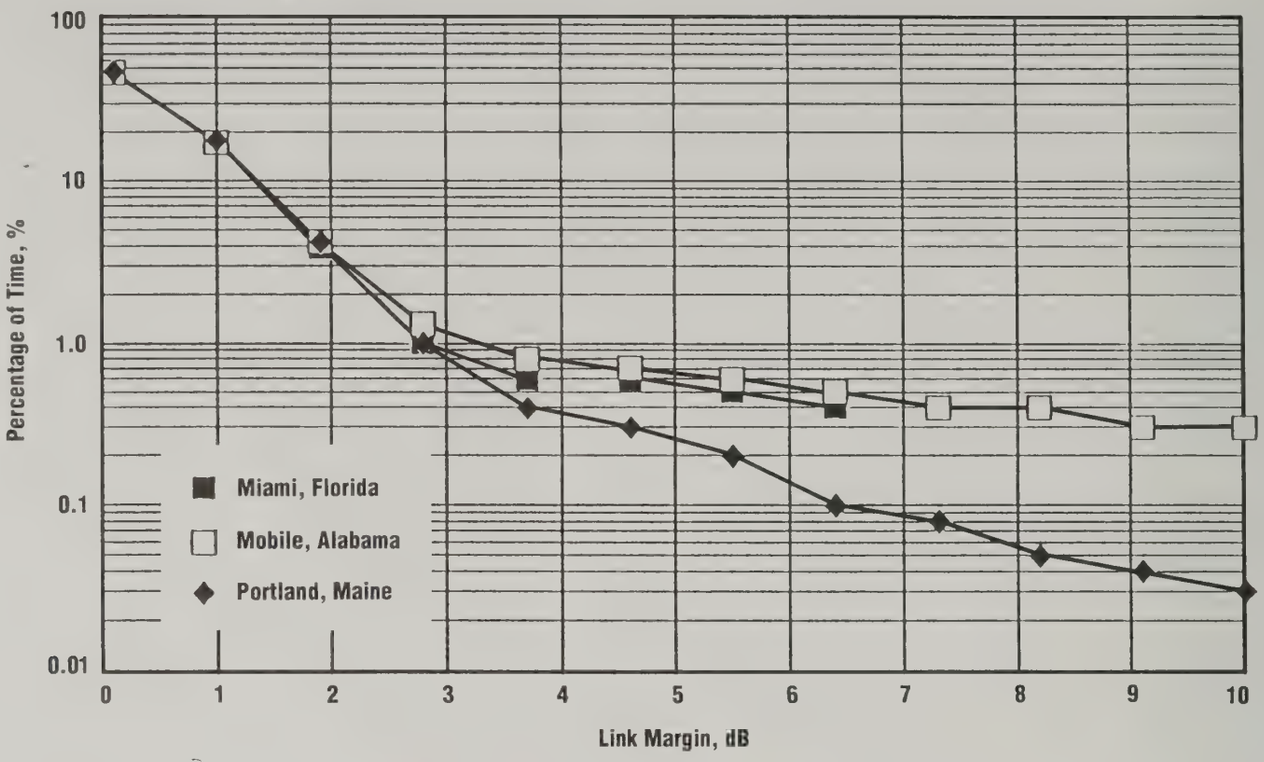

Figure 5. Percentage of time total link attenuation exceeds link margin for the forward link.

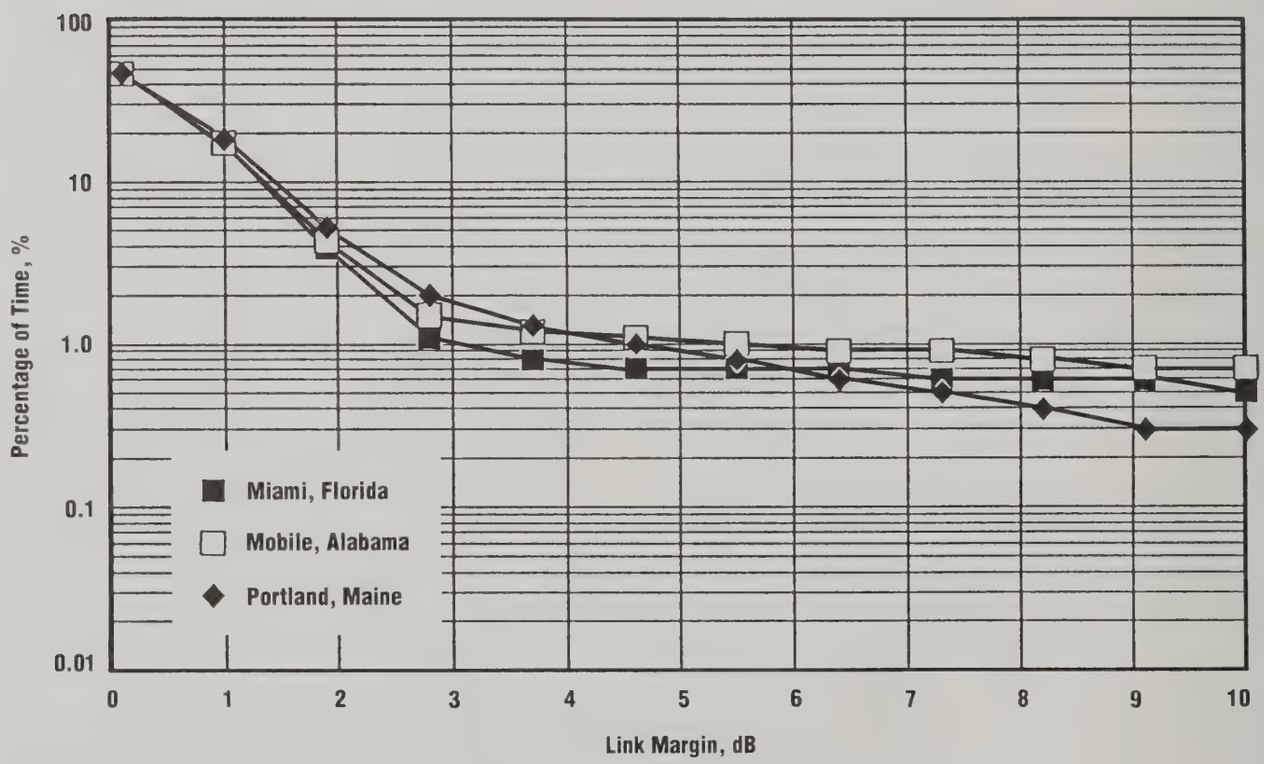

Figure 6. Percentage of time total link attenuation exceeds link margin for the return link.

Table 3. Return link budget for basic personal terminals (4.8 kbps voice, clear sky, 1.0^{-3} BER)

Link parameter	User to satellite	Satellite to supplier
Transmit power dBW	–7.8	–15.0
Circuit loss, dB	–0.5	–0.5
Antenna gain, dBi	22.8	26.9
EIRP, dBW	14.5	11.4
Space loss, dB	–214.0	–210.5
Frequency, GHz	30.0	20.0
Edge of beam loss, dB	–4.0	–3.0
Receive antenna gain, dBi	52.5	57.5
Received signal power, dBW	–155.0	–146.1
System noise temperature, dBK	29.1	27.2
Received N_o, dBW/Hz	–199.5	–201.5
Received C/N_o, dB-Hz	44.5	55.3
End-to-end C/N_o, dB-Hz	—	43.9
Modem/radio loss, dB	—	–1.0
Required Eb/N_o, dB	—	3.0
Data rate, kbps	4.8	4.8
Required C/N_o, dB-Hz (voice)	—	39.8
Link margin, dB	—	3.0
Link variation statistics mean, dB	—	0.0
1-σ Link margin deviation, dB	—	1.0

contributions of downlink rain attenuation, service availability for the return link is estimated using Equations (1–5); the results are shown in Figure 6. Rain attenuation and link variation statistics are tabulated in Table 4. Figure 6 also shows that the 3-dB link margin would be adequate 98% of the time.

Higher Availability for Critical Services

Based on these analyses, basic personal communications services are available at the nominal data rate of 4.8 kbps. However, some services offered by PASS — such as emergency communications — require a higher availability, and the variable data rate scheme is designed to satisfy these needs. By reducing the data rate from 4.8 to 2.4 kbps, link availability can be increased to about 99%, as indicated in Figures 5 and 6. A further reduction below 2.4 kbps would

Table 4. Key parameter values for the return link

Key parameter	Miami, Florida	Mobile, Alabama	Portland, Maine
$\mu_{\ln(y)}$, dB	12.9	10.3	2.8
σ_y, dB	0.98	0.89	0.89
P_o, %	0.9	1.3	3.2
μ_x, dB	0.0	0.0	0.0
σ_x, dB	1.0	1.0	1.0

result in even higher service availability, although the improvement becomes increasingly negligible.

Conclusion

Based on the three locations examined, service availability for PASS has been estimated to be 98% at 4.8 kbps and 99% at 2.4 kbps. Although analyses of additional locations are needed to fully establish PASS's service reliability, the analysis of the three selected locations — all areas with heavy rain — has provided a quick assessment of PASS's rain compensation strategy and resulting service quality. The results indicate that the impacts of rain attenuation for PASS-like systems are moderate and can be mitigated without the need for complex onboard satellite baseband processing technologies.

The foregoing analysis is based on annualized rain statistics. The effects of worst-month rain statistics are addressed in a separate article in this issue.

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[2] P. Estabrook, J. Huang, W. Rafferty and M. Sue, "A 20/30 GHz Personal Access Satellite System Design," International Conference on Communications, Boston, MA, June 11–14, 1989.

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The Effectiveness of PASS Rain Compensation Techniques Based on Worst-Month Statistics

B. K. Levitt, JPL

In [1], Sue discusses a proposed variable data rate rain compensation scheme for the Personal Access Satellite System (PASS). Based on computations of *annualized* average link availability, he concludes that the benefit of this compensation technique is insufficient to justify the required increase in system complexity. However, this article demonstrates that an extension of his analysis to worst-month rainfall conditions suggests the opposite conclusion.

Worst-Month Analysis

In the absence of rain, Sue assumes that the clear-sky link margin *variation* x (dB) in the forward (supplier-to-user) or return (user-to-supplier) direction can be regarded as a Gaussian random variable (GRV) with mean zero and standard deviation σ_1, resulting in the probability density function (pdf):

$$p(x) = \frac{1}{\sigma_1 \sqrt{2\pi}} e^{-\frac{x^2}{2\sigma_1^2}}; \quad -\infty < x < \infty \qquad (1)$$

The rationale for the Gaussian characteristic is that the variation in the link margin results from the combined effects of the variations in the individual link budget components (antenna pointing error, atmospheric propagation loss, transmit power, etc.). The standard deviations of each of these contributing parameters are combined on a root-sum-square (RSS) basis to yield σ_1; PASS link budgets traditionally assume that $\sigma_1 = 1$ dB.

Rain anywhere along the forward or return propagation paths will degrade the corresponding link margin by attenuating the signal and increasing the system noise temperature; this latter effect is ignored in the analysis below. Uplink power control in the forward direction almost completely mitigates the effect of any uplink rain attenuation. Because of the relatively low user terminal transmit power and antenna gain, the return link margin in the presence of rain is limited by the uplink rain attenuation. *Consequently, for both the forward and return directions, rain attenuation in the path between the user terminal and the satellite overshadows any corresponding fading in the satellite–supplier leg.*

When it is raining anywhere along the user–satellite propagation path (denoted by event R), x must be augmented by an additive

rain attenuation term y (dB). This factor is usually assumed to be a log-normal random variable conditioned on R [2] with pdf:

$$p(y|\mathrm{R}) = \frac{1}{\sigma_2 y \sqrt{2\pi}} e^{-\frac{(\ln y - \mu_2)^2}{2\sigma_2^2}} \quad ; \quad 0 < y < \infty \tag{2}$$

where μ_2 and σ_2 are the mean and the standard deviation of the GRV, $\ln y$.

Then the total link margin attenuation $z = x + y$ (dB) conditioned on R has a pdf that is simply the convolution of the pdfs for x and y:

$$p(z|\mathrm{R}) = \frac{1}{2\pi\sigma_1\sigma_2} \int_0^\infty d\alpha \left(\frac{1}{\alpha}\right) e^{-\frac{(z-\alpha)^2}{2\sigma_1^2}} e^{-\frac{(\ln \alpha - \mu_2)^2}{2\sigma_2^2}} \quad ; \quad -\infty < z < \infty \tag{3}$$

Finally, removing the conditional constraint, the overall pdf of z is given by

$$p(z) = (1 - P_0)\, p(x)\big|_{x=z} + P_0\, p(z|\mathrm{R}); \; P_0 \equiv \Pr[\mathrm{R}] \tag{4}$$

In [1], Sue used the service availability of the PASS forward and return links as a measure of communication system performance for a given data rate. For example, if the nominal clear-sky (i.e., $z = 0$ dB) forward or return link margin is ρ dB for a particular data rate, Sue defines the corresponding link availability as the probability $\Pr[z < \rho]$ that the link margin is positive. Since the link availability hopefully is close to 100%, it is more accurate to calculate the probability of a link *outage*:

$$\Pr[z > \rho] = (1 - P_0) \int_\rho^\infty dx\, p(x) + P_0 \int_\rho^\infty dz\, p(z|\mathrm{R}) \tag{5}$$

Using Equations (3) and (5), the link outage probability implies a double integration in the second term that must be computed using time-consuming numerical techniques. However, it can be greatly simplified by interchanging the order of integration in that term and by introducing the Gaussian complementary error function [3]:

$$Q(x) \equiv \frac{1}{\sqrt{2\pi}} \int_x^\infty dz\ e^{-\frac{z^2}{2}} \qquad (6)$$

which can be accurately computed using approximations in [4]. Then, after some changes of variables, it can be shown that Equation (5) reduces to

$$\Pr[z > \rho] = (1 - P_0)\ Q\left(\frac{\rho}{\sigma_1}\right) + \frac{P_0}{\sqrt{2\pi}} \int_{-\infty}^\infty d\alpha\ e^{-\frac{\alpha^2}{2}}\ Q\left(\frac{\rho - e^{\mu_2 + \sigma_2 \alpha}}{\sigma_1}\right) \qquad (7)$$

Before proceeding, a couple of observations should be made. An interesting special case is the limit as σ_1 approaches zero. This is equivalent to eliminating the Gaussian variation in the clear-sky link margin since the pdf of x in Equation (1) becomes a delta function at $x = 0$, $\delta(x)$. Then the convolution of the pdf of x and the conditional pdf of y is simply the latter, i.e., $p(z|R)$ becomes $p(y|R)$. It follows from Equations (2) and (6) that Equation (5) reduces to

$$\Pr[z > \rho] \xrightarrow[\sigma_1 \to 0]{} (1 - P_0) \int_\rho^\infty dx\ \delta(x) + P_0 \int_\rho^\infty dy\, p(y|R) \qquad (8)$$

$$= P_0\, Q\left(\frac{\ln \rho - \mu_2}{\sigma_2}\right);\ \rho > 0 \text{ dB}$$

which is exactly the simplified closed-form expression that would result from purely log-normal link margin variations due only to rain attenuation. This same result can be derived directly from Equation (7) by noting that the Q functions approach unit step functions in the limit of negligibly small σ_1:

$$Q\left(\frac{x}{\sigma_1}\right) \xrightarrow[\sigma_1 \to 0]{} u_{-1}(-x) = \begin{cases} 1; & x < 0 \\ 0; & x > 0 \end{cases} \qquad (9)$$

Replacing the Q functions by the appropriate unit step functions in Equation (7) again yields Equation (8).

The second observation is that in the region $\rho >> \sigma_1$, for arbitrary σ_1, the link outage probability of Equation (7) also approaches the closed-form expression of Equation (8). One way to see this is to start with Equation (4) and argue that

$$p(z) \approx P_0\, p(y|\mathrm{R})\,|_{\,y=z};\ z >> \sigma_1 \qquad (10)$$

from which it follows that $\Pr[z > \rho]$ asymptotically satisfies Equation (8). Alternatively, it can be shown directly from Equation (7), but this will not be proven in this article. This limiting behavior is also illustrated in Figure 1.

In [1], Sue used Manning's rain attenuation model based on *annualized* rainfall statistics [2] to compute P_0, μ_2 and σ_2 for several user terminal locations.[1] He then computed the forward and return link availabilities for each of these locations when the data rate is fixed at R_b = 4.8 kbps for each user and the required bit error rate (BER) is 10^{-3}, which yields the nominal clear-sky link margin ρ = 3 dB. *Sue's conclusion was that in all cases the link availability would exceed 98%, obviating the need to reduce the data rate to compensate for rain attenuation.* The problem with this assessment is that it is only true on an annualized average basis. During the rainy season in a given user terminal location, the performance can be seriously degraded.

For example, consider the return link for a user terminal in Portland, Maine — one of the highest rainfall locations examined in [1]. Inserting the required inputs into Manning's model — i.e., PASS satellite at 95° W longitude; user terminal at 70.2° W longitude, 43.7° N latitude and 25 ft above sea level; average annual rainfall of 43.52 in. and uplink frequency of 30 GHz — we find that P_0 = 3.176%, μ_2 = 1.040 and σ_2 = 0.899. Using these parameters with σ_1 = 1 dB and ρ = 3 dB in Equation (7) indeed shows that the annualized average link outage probability is only 1.71%, which is equivalent to a link availability of 98.3%. For comparison

[1]Manning's notation in [2] is different from Sue's. The translation from Sue to Manning is $P_0 = P_0(L,\theta)$, $\mu_2 = \ln A_m$ (A_m is the *median* link attenuation), and $\sigma_2 = \sigma_{\ln A}$.

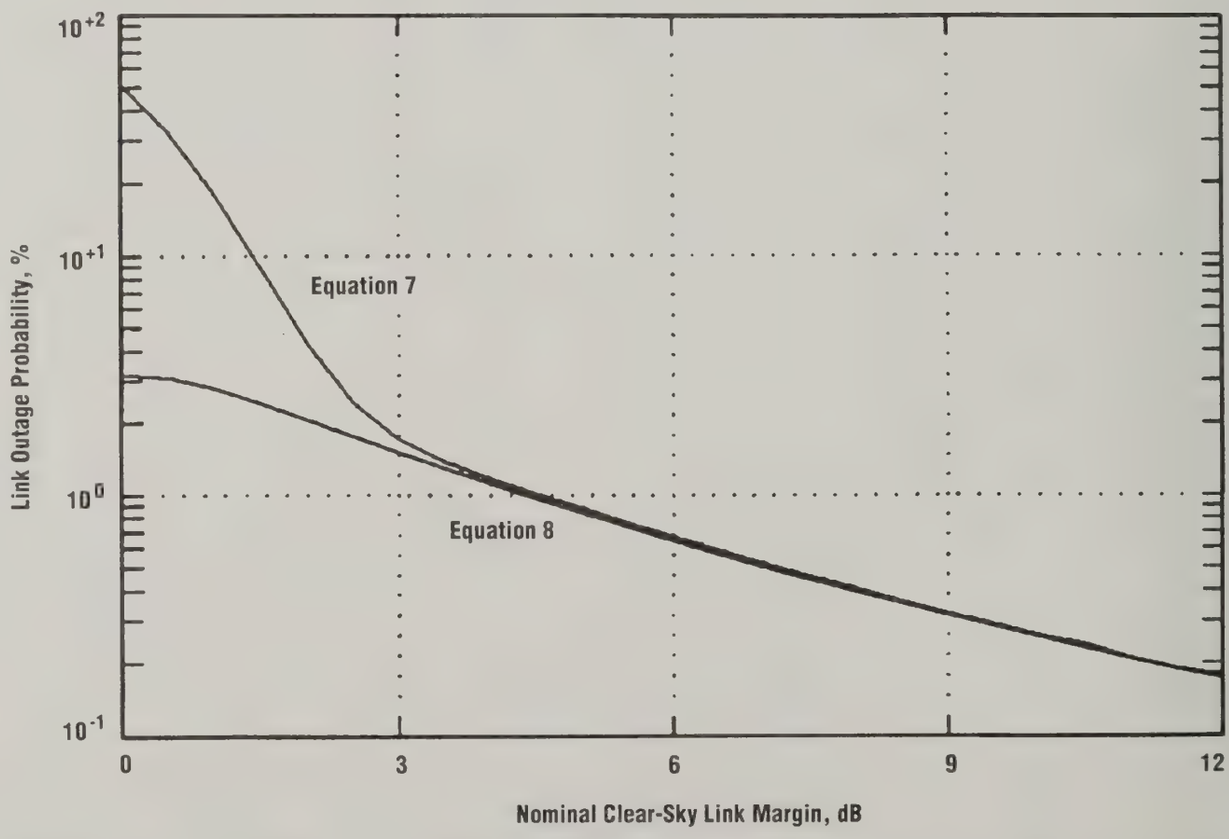

Figure 1. Comparison between exact Equation (7) and asymptotic Equation (8) expressions for return link outage probability as a function of nominal clear-sky link margin based on annualized rainfall statistics for user terminal in Portland, Maine.

with Figure 6 in [1], the expressions for link outage probability in Equations (7) and (8) are plotted as functions of the nominal clear-sky link margin in Figure 1; it is evident that Equation (7) does asymptotically equal Equation (8) for values of ρ in excess of approximately $4\sigma_1 = 4$ dB.

At this time, there are no definitive data regarding performance degradation during Portland's rainy season. The only currently available data point is a Comité Consultatif International des Radiocommunications (CCIR) study that derived a general empirical relationship between the worst-month and annual rain attenuation probabilities [5–7]:

$$P_0^* = (3.45\ P_0)^{0.87} \qquad (11)$$

where P_0^* denotes the worst-month statistic.

Applying Equation (11) to the Portland example, we find that the worst-month parameter $P_0^* = 14.61\%$, which is a significant increase (a factor of 4.6) over the annualized average P_0. For $\rho = 3$ dB, replacing P_0 with P_0^* in Equation (7) raises the link outage probability to 7.39% in the worst month (corresponding to a worst-month link availability of only 92.6%). For comparison with arbitrary values of ρ, Equation (7) is plotted in Figure 2 for both annualized and worst-month statistics. From Equation (8), it is obvious that the asymptotic increase in link outage probability for large ρ is simply the ratio P_0^*/P_0 based on this rudimentary analysis.

In fact, the worst-month link performance may be further degraded. Not only would we expect that the probability of rain attenuation P_0 is increased during the rainy season, but the *amount* of rain attenuation will also be greater than the annual average, i.e., μ_2 and σ_2 will increase corresponding to the increased likelihood of severe fades.

Rain Compensation Benefits

Let us now return to the issue of the utility of a variable data rate rain compensation scheme for PASS using this simplistic worst-month analysis. Suppose we reduce the user data rate R_b from 4.8 kbps to 2.4 kbps; neglecting implementation losses, that raises the nominal clear-sky return link margin to $\rho = 6$ dB. Using Equation (7), or even Equation (8), with this increased ρ and P_0^*, we compute that the link outage probability drops to 3.07% (i.e., link availability rises to 96.9%). Performing a similar exercise for $R_b = 1.2$ kbps, the link outage probability falls to 1.49% (availability increases to 98.5%). This suggests the following idealized PASS rain compensation algorithm (RCA):

$$R_b = \begin{cases} 4.8 \text{ kbps}; & z < 3 \text{ dB} \\ 2.4 \text{ kbps}; & 3 < z < 6 \text{ dB} \\ 1.2 \text{ kbps}; & z > 6 \text{ dB} \end{cases} \qquad (12)$$

which produces the link margin characteristic shown in Figure 3. As calculated above, this would — subject to more definitive statistics — increase the worst-month link availability to 98.5% in comparison with only 92.6% for a fixed-rate system at 4.8 kbps. This increased performance should arguably justify the additional expense and complexity of the RCA. Of course, if the fixed-rate implementation used $R_b = 1.2$ kbps instead of 4.8 kbps, the link *availability* would be precisely the same as that provided by the RCA *on an annualized or worst-month basis.* The difference is that the average link *throughput* would be reduced by approximately 75% relative to the RCA or $R_b \equiv 4.8$ kbps fixed-rate system since clear-sky conditions can be expected to prevail most of the time.

Incidentally, average link throughput is not an illuminating parameter for demonstrating the advantages of an RCA over a fixed-rate system. For example, the 4.8 kbps fixed-rate system has a worst-month average link throughput of

$$\left(\frac{100 - 7.39}{100}\right) 4.8 = 4.45 \text{ kbps} \qquad (13)$$

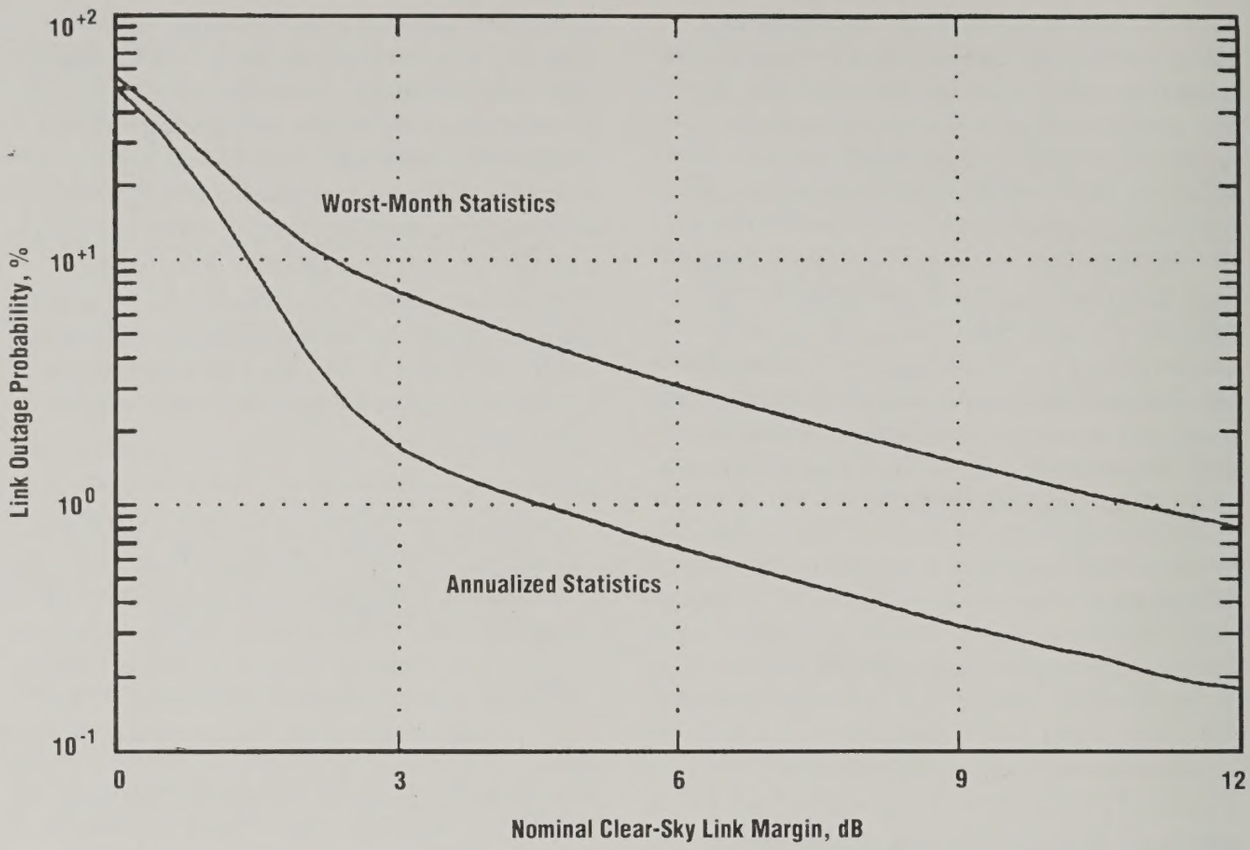

Figure 2. Comparison between worst-month and annualized average return link outage probability as a function of nominal clear-sky link margin for user terminal in Portland, Maine.

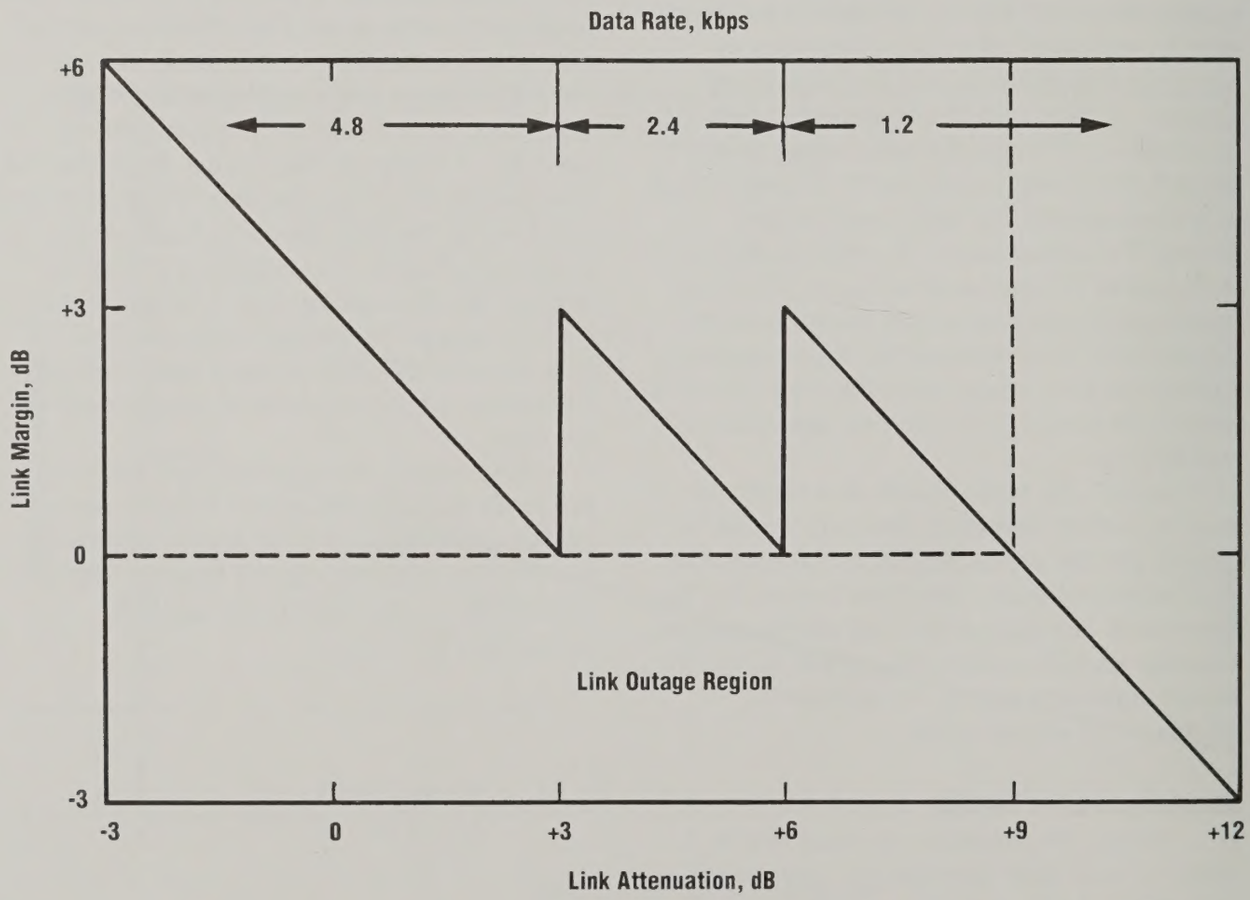

Figure 3. Variation of link margin with link attenuation for idealized PASS rain compensation algorithm specified in Equation (12).

By comparison, the RCA specified in Equation (12) has a worst-month average link throughput of

$$\left(\frac{100-7.39}{100}\right) 4.8 + \left(\frac{7.39-3.07}{100}\right) 2.4 + \left(\frac{3.07-1.49}{100}\right) 1.2 = 4.57 \text{ kbps} \quad (14)$$

which only represents a 3% improvement in this particular figure of merit.

It should be noted that one key aspect of an RCA that is missing in this analysis is the problem of estimating the link attenuation z (which is, of course, actually a random process rather than a random variable). In general, this implies the derivation of statistically accurate rain attenuation estimates based on observations of the forward link received signal-to-noise ratio and/or the received pilot signal strength if the satellite–user downlink includes a pilot. Manning has begun to look at the pilot level problem using a minimum mean-square-error criterion [8], and it is decidedly non-trivial.

Conclusion

Sue's PASS link availability analysis has been extended from annualized to worst-month rainfall conditions. In the latter case, it has been demonstrated that a variable data rate rain compensation scheme can provide significant performance improvements. As an example, for a PASS user terminal at Portland, Maine, the RCA of Equation (12) results in the following annualized and worst-month average link availabilities in comparison with a fixed-rate system at 4.8 kbps:

	Average Link Availability, %	
Statistical basis	**With RCA Pr[z < 9 dB]**	**Without RCA Pr[z < 3 dB]**
Annual rain data	99.7	98.3
Worst-month rain data	98.5	92.6

It is clear that the annualized average link availability for a PASS user terminal in Portland, Maine, with or without rain compensation, meets the PASS design goal of 95–98% for personal voice communications [1]. However, some form of rain compensation such as the proposed variable data rate RCA is needed for worst-month rain operations to satisfy minimum performance specifications.

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AGARD Symposium on Wave Propagation

The 47th Symposium of the Electromagnetic Wave Propagation Panel of AGARD (Advisory Group for Aerospace Research and Development) was held at Rethymnon, Crete, Greece, October 15–19, 1990. Fifty representatives from more than 10 NATO countries attended this symposium on "The Use or Reduction of Propagation and Noise Effects in Distributed Military Systems." The symposium was organized into six sessions covering the following topics: limitations of the medium in distributed systems, meteor trails, jamming and noise on distributed systems, radar systems, distributed systems, and one classified session.

Dr. Faramaz Davarian from JPL presented a paper, "The NASA Radiowave Propagation Program," which discussed the purpose of NASA's propagation program — namely, to support studies in civilian applications and commercial space systems. Dr. Davarian also presented the recommendations made by the NASA review committees. According to the committees, more interaction between the propagation program representatives and their military counterparts should be encouraged to enhance research efforts and reduce possible work duplication in these areas.

A majority of the symposium papers addressed terrestrial communications systems; many of these papers discussed the effect of the ionosphere on wave transmission and meteor burst communications.

Several papers focused on propagation in mobile channels. One notable paper on this subject was presented by R. Harris from the United Kingdom, who discussed the multipath-induced Doppler effect in aeronautical links. Harris proposed suppressed-carrier transmission to reduce the adverse effects of the propagation channel. Other papers on propagation studies included a report from Germany that proposed using 60-GHz systems for secure short-range communications. The presence of an oxygen band in the vicinity of 60 GHz provides a natural protection for a short-range communications system. Measurements made at 61 GHz were reported.

Papers on systems aspects included a presentation by a Norwegian scientist on low-noise receiving systems. This presentation included a tutorial on how to compute the noise figure of a receiver and the effect of antenna noise temperature on the noise figure.

One of the highlights of the symposium was a visit to the NATO Missile Firing Installation (NAMFI), where the symposium guests viewed a film on NAMFI's activities followed by a demonstration of a missile firing.

According to Dr. Davarian, this year's symposium was not only informative, but it offered a valuable opportunity to form closer ties between NASA's propagation program and AGARD.

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JPL 410-33-1 4/91